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New rest wavelength determinations for 7 mid-infrared fine structure lines by ISO-SWS¹

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ABSTRACT

Observations of the planetary nebulae NGC 6302, NGC 6543 and NGC 7027 by the Short Wavelength Spectrometer (SWS) on board the Infrared Space Observatory (ISO) have been used to determine rest wavelengths of spectral lines. We report on improved accuracies for wavelengths of 7 mid-infrared ionic fine structure lines.

Subject headings: Atomic data — Line: identification — Infrared: ISM: lines and bands

1. Introduction

Mid infrared atomic fine structure lines are important probes for a variety of astrophysical environments like planetary nebulae (e.g., Beintema et al. 1996), shocked regions (e.g., Oliva et al. 1999) and galaxies (e.g., Lutz et al. 2000). Due to their low magnetic dipole transition probabilities the lines are usually optically thin ($\tau = 10^{-2}$ to a few) and measurements of these lines give handles on luminosities and spatial distribution of abundant atoms

¹Based on observations made with ISO, an project of ESA with participation of ISAS and NASA, and the SWS, a joint project of SRON and MPE with contributions from KU Leuven, Steward Observatory and Phillips Laboratory.

and ions. In addition they provide also valuable information on the density, temperature and ionization structure of targets with little or no dependence on dust extinction that hampers observations in the visible. Accurate laboratory measurements of highly ionized species are difficult and line rest wavelengths are mostly based on energy level differences reconstructed from UV and optical spectroscopy. The knowledge of accurate rest wavelengths of these lines will enhance their diagnostic value for many spectroscopic studies in the mid-infrared wavelength range.

New wavelength determinations by the Short Wavelength Spectrometer (SWS; de Graauw et al. 1996) on board the Infrared Space Observatory (ISO; Kessler et al. 1996) have been reported by Feuchtgruber et al. 1997 (hereafter paper I). The observations therein were taken early during the ISO mission and the subsequent analysis was focused mainly on bright lines. Long integration observations on NGC 6302, NGC 6543 and NGC 7027 obtained later during the operational lifetime of ISO revealed another 7 lines where SWS data provide improved accuracies on their rest wavelengths. Thus, the present work represents an extension of paper I towards fainter lines. Transitions from [Cl IV], [Cl V], [Ca V], Ca [VII] and [Al VI] have been measured in SWS AOT06 grating mode, while the 21.8 μm line of [Ar III] has been detected with the SWS Fabry-Perot (FP), improving significantly on its accuracy as compared to the SWS grating observation reported in paper I.

The accuracy of the SWS wavelength calibration has been established initially by Valentijn et al. 1996 down to an uncertainty of 0.5-1.0 steps of the grating scanner. This value, translated from its instrumental unit into wavelength, typically corresponds to $\lambda/\Delta\lambda = 1 \times 10^4$. The nominal 2 steps uncertainty of the FP at 21.8 micron correspond to $\lambda/\Delta\lambda = 1 \times 10^5$. While the FP wavelength calibration has proven to be stable throughout the whole ISO mission, the SWS grating wavelength calibration has shown a slight shift in time (< 0.1 step/month). Regular calibration observations of the internal SWS grating calibration source and external astronomical wavelength calibration targets have however allowed to maintain the initial accuracy by interpolation between the various measurements. For more details regarding the accuracy of wavelengths in SWS observations see paper I and Valentijn et al. 1996.

2. Observations and data reduction

We have analyzed observations, taken in SWS AOT06 grating mode of the planetary nebulae NGC 6302 and NGC 7027. NGC 6543 has been observed in SWS AOT07 Fabry-Perot mode. The rich SWS spectra of these targets are discussed e.g. by Beintema et al. 1996, Pottasch et al. 1996, Beintema & Pottasch 1999 and Pottasch & Beintema 1999. Here,

Table 1. Summary of new wavelength determinations

Ion	Transition $u - l$	Vac. Wavelength* [μm]	Rest wavenumber* [cm^{-1}]	χ_{lower} [eV]	χ_{upper} [eV]	Obs. Date	Tar
[Al VI]	$^3\text{P}_1$ - $^3\text{P}_2$	$3.65971 \pm (62)$	$2732.46 \pm (46)$	153.83	190.48	1997-Feb-20 ^a	NGC
[Ca VII]	$^3\text{P}_2$ - $^3\text{P}_1$	$4.0858 \pm (12)$	$2447.5 \pm (7)$	108.78	127.20	1997-Feb-20 ^a	NGC
[Ca V]	$^3\text{P}_1$ - $^3\text{P}_2$	$4.15937 \pm (62)$	$2404.21 \pm (36)$	67.27	84.50	1996-Oct-19 ^a	NGC
[Cl V]	$^2\text{P}_{3/2}$ - $^2\text{P}_{1/2}$	$6.70667 \pm (62)$	$1491.05 \pm (14)$	53.46	67.82	1996-Oct-19 ^a	NGC
[Cl IV]	$^3\text{P}_2$ - $^3\text{P}_1$	$11.7619 \pm (11)$	$850.203 \pm (79)$	39.61	53.46	1996-Oct-19 ^a	NGC
[Cl IV]	$^3\text{P}_1$ - $^3\text{P}_0$	$20.3107 \pm (21)$	$492.351 \pm (51)$	39.61	53.46	1997-Feb-20 ^a	NGC
[Ar III]	$^3\text{P}_0$ - $^3\text{P}_1$	$21.8302 \pm (3)$	$458.081 \pm (6)$	27.63	40.74	1997-Feb-11 ^b	NGC

^aGrating scan

^bFabry-Perot line scan

*Numbers in brackets give errors on last decimals

Note. — χ_{lower} and χ_{upper} denote excitation and ionization potentials

we focus exclusively on wavelength determination and report only about those lines observed by SWS for which we could improve on the accuracy of the rest wavelengths.

The data reduction of all measurements was done using the SWS Interactive Analysis software (SIA; Wieprecht et al. 1998) package on ISO pipeline products of version OLP 8.4. Particular attention has been paid to remove instrumental fringing in the wavelength range between $12\ \mu\text{m}$ and $29\ \mu\text{m}$ by the dedicated fourier filtering modules of SIA. The same procedure was used as for paper I. Gaussian fits to the spectral lines provided the center wavelengths, which were corrected for the heliocentric radial velocity and for the mean ISO radial velocity. Typical velocity changes during an observation were less than $0.3\ \text{km/s}$, so could be neglected. The observed profiles of all lines with new wavelengths are presented in Fig. 1.

2.1. Use of reference lines

Small pointing errors and spatial inhomogeneities of the targets can induce apparent velocity shifts in SWS grating data. We have corrected for this effect using reference lines of accurately known wavelengths, observed in the same SWS aperture during the same observation. Details of this strategy are given in paper I and will not be repeated here. Although at similar accuracy, some reference lines with rest wavelengths determined in paper I have been used (see Table 2), to improve on fixing the reference frame and to illustrate the good agreement with the more accurate reference lines.

The new wavelength determinations together with some other line properties are summarized in Table 1. The framework of fine structure and hydrogen or helium recombination reference lines which were used for the individual observations of our targets is listed in Table 2. The offsets reflect the pointing error and the effects of the spatial structure of the source of the particular observation. Together with the uncertainty of the literature wavenumber, the ‘SWS uncertainty’ in Table 2 is propagated into the uncertainty of new wavelength determinations that are tied to this line.

Apart from literature wavenumbers, Table 2 also includes a rest wavenumber for NGC 6302 which was determined during the independent observation by the SWS FP on NGC 6543.

2.2. NGC 6302

The SWS grating observation of NGC 6302 has been carried out on 1997 February 20. The total integration time has been 8532 s. Beintema & Pottasch (1999) have presented

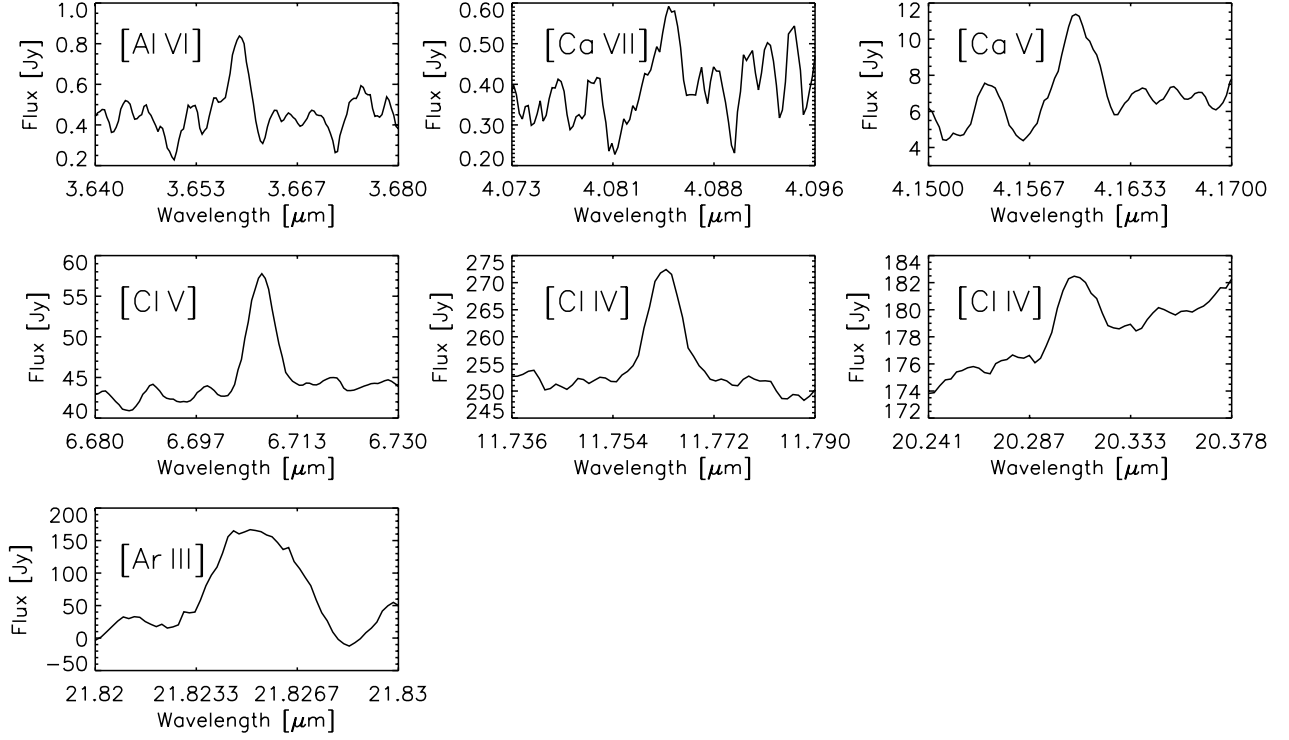


Fig. 1.— Observed fine structure lines: [Al VI], [Ca VII] and [Cl IV] ($20.3 \mu\text{m}$) from NGC 6302; [Ca V], [Cl V] and [Cl IV] ($11.76 \mu\text{m}$) from NGC 7027; [Ar III] from NGC 6543

the first analysis of this AOT SWS06 observation and provided an extensive line list for the SWS wavelength range. From this observation we derived improved rest wavelengths for the three lines reported in table 1. The [Cl IV] line has escaped the analysis by Beintema & Pottasch, who quote an upper limit to the line flux. For the faint lines of [Al VI] and [Ca VII] the uncertainties of the wavelength determinations are dominated by detector noise.

From the analysis of the set of reference lines (see table 2), measured at similar wavelength and with the same SWS aperture, the observed lines in NGC 6302 had to be shifted by -4km s^{-1} for [Cl IV] and -26km s^{-1} for [Al VI] and [Ca VII] with respect to the heliocentric velocity of $-39 \pm 2\text{km s}^{-1}$ given by Acker et al. (1992), probably due to a pointing error. Note that a pointing error may translate into different shifts for the short wavelength and long wavelength sections of SWS because their beam profiles are centered on slightly different positions on the sky (Salama 2000), and since the velocity shift corresponding to a given angular shift differs for different order and aperture combinations.

2.3. NGC 6543

The ionic line from [Ar III] at $21.83\text{ }\mu\text{m}$ has been detected by the ISO SWS FP during an observation of 6750 s on 1997 February 11. The wavelengths from the [Ne III] line at $15.5\text{ }\mu\text{m}$ and of the [S III] line at $18.71\text{ }\mu\text{m}$ have been remeasured during the same observation. Both reproduce the results from paper I within their quoted uncertainties, confirming the assumption of sufficient velocity and spatial averaging across the target through the SWS slit sizes, since the [Ne III] wavelength has been originally determined on NGC 7027 and the [S III] line has been observed at a different position angle of the SWS slit on NGC 6543. The heliocentric velocity correction of $-66.1 \pm 0.4\text{ km/s}$ for NGC 6543 has been taken from Schneider et al. (1983). The determined rest wavelength for the [Ar III] transition is in agreement with the SWS grating result from paper I, however its accuracy is now significantly improved.

2.4. NGC 7027

The planetary nebula NGC 7027 has been observed with SWS on 1996 October 19. The total integration time of the AOT06 observation has been 7962 s. New wavelength have been determined for ionic lines of [Ca V], [Cl IV] and [Cl V]. The data are presented in Fig. 1 and their new rest wavelengths in Table 1. For this observation we found a mean shift of $+24\text{km s}^{-1}$ of the reference lines (Table 2) with respect to the heliocentric velocity

of $+8.8 \pm 0.6 \text{ km s}^{-1}$ from Schneider et al. (1983).

3. Conclusions

Extending the results of paper I towards fainter lines, the ISO Short Wavelength Spectrometer has been used to obtain new rest wavelengths for 7 mid-infrared fine structure lines. 6 of these are from species with lower ionization potentials $\geq 40 \text{ eV}$, detectable in high excitation planetary nebulae and active galactic nuclei.

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Table 2. Summary of reference wavenumbers. See section 2.1 and paper I for explanations.

Obs. Date	Target	Ion	Transition $u - l$	Ref. Wavenumber [cm ⁻¹]	Offset ^a [cm ⁻¹]	SWS uncertainty ^b [cm ⁻¹]	
1997-Feb-20	NGC 6302	H ₂ O(5)	1 - 0	3091.20± ≤0.03	0.05	0.19	
1997-Feb-20	NGC 6302	HI	9 - 5	3033.07± ≤0.03	0.08	0.19	v
1997-Feb-20	NGC 6302	HI	8 - 5	2673.40± ≤0.03	0.14	0.28	v
1997-Feb-20	NGC 6302	[Mg IV]	² P _{1/2} - ² P _{3/2}	2228.82±0.15	-0.02	0.15	F
1997-Feb-20	NGC 6302	[Ar VI]	² P _{3/2} - ² P _{1/2}	2207.74±0.15	0.02	0.15	F
1997-Feb-20	NGC 6302	[K III]	² P _{1/2} - ² P _{3/2}	2165.43±0.22	0.07	0.22	F
1997-Feb-20	NGC 6302	HI	7 - 5	2148.79± ≤0.02	-0.06	0.14	v
1997-Feb-20	NGC 6302	[Na VII]	² P _{3/2} - ² P _{1/2}	2134.60±0.15	0.02	0.15	F
1997-Feb-20	NGC 6302	HeII	8 - 7	2099.29± ≤0.02	-0.07	0.13	v
1997-Feb-20	NGC 6302	[Mg V]	³ P ₁ - ³ P ₂	1782.58±0.20	0.02	0.20	F
1997-Feb-20	NGC 6302	[Ar II]	² P _{1/2} - ² P _{3/2}	1431.5831±0.0007	-0.11	0.13	
1997-Feb-20	NGC 6302	[S III]	³ P ₂ - ³ P ₁	534.387±0.005	0.008	0.03	
1997-Feb-20	NGC 6302	[Ar III]	³ P ₀ - ³ P ₁	458.081±0.006	0.002	0.04	
1997-Feb-20	NGC 6302	[Ne V]	³ P ₂ - ³ P ₁	411.226±0.006	-0.007	0.04	F
1997-Feb-20	NGC 6302	[O IV]	² P _{3/2} - ² P _{1/2}	386.245±0.005	-0.001	0.03	F
1996-Oct-19	NGC 7027	HI	12 - 6	2284.95±0.02	-0.03	0.15	v
1996-Oct-19	NGC 7027	HI	7 - 5	2148.79±0.02	0.06	0.15	v
1996-Oct-19	NGC 7027	HI	9 - 6	1692.56±0.02	0.09	0.18	v
1996-Oct-19	NGC 7027	HI	6 - 5	1340.51±0.01	-0.04	0.11	v
1996-Oct-19	NGC 7027	[Ar II]	² P _{1/2} - ² P _{3/2}	1431.5831±0.0007	0.00	0.13	
1996-Oct-19	NGC 7027	[S III]	³ P ₂ - ³ P ₁	534.387±0.005	0.006	0.03	
1996-Oct-19	NGC 7027	[Ne V]	³ P ₁ - ³ P ₀	411.226±0.006	-0.006	0.04	F
1996-Oct-19	NGC 7027	[O IV]	² P _{3/2} - ² P _{1/2}	386.245±0.005	0.002	0.03	F
1996-Oct-19	NGC 7027	[Ar V]	³ P ₂ - ³ P ₁	1265.57±0.04	-0.08	0.10	
1996-Oct-19	NGC 7027	[Ar III]	³ P ₁ - ³ P ₂	1112.176±0.015	-0.01	0.07	
1996-Oct-19	NGC 7027	[S IV]	² P _{3/2} - ² P _{1/2}	951.430±0.01	0.013	0.05	

^aDifference between observed and literature wavenumber of the reference line.

^bMeasurement uncertainty in the SWS observation of the reference line.

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